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I, Toyu Yazaki, hereby declare that I am a professional interpreter and translator, with twenty (20) years of professional experience, and am knowledgeable of and well acquainted with the Japanese language and the English language . The document attached hereto is to the best of my ability, knowledge and expertise a correct English translation of the original document written in the Japanese language.

I declare under penalty of perjury under the laws of the United States that the foregoing is true and correct. Executed this 18th day of May 2002 at San Francisco, California.

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(57) Abstract

Object: To increase the level of the third-order harmonic components of motor speed electromotive force waveform that serve as the source of rotor position detection signal.

Construction: Main permanent magnet 2b is disposed close to rotor shaft 2a of rotor 2 and auxiliary permanent magnet 2d is disposed near the surface of rotor 2 corresponding to the end of main permanent magnet 2b in the direction of rotation.

[Illustration]

1. Armature

1b. Armature winding

2. Rotor

2a. Rotor shaft

2b. Main permanent magnet

2d. Auxiliary permanent magnet

Claims

Claim 1: In a brushless DC motor wherein rotor (2) containing permanent magnet (2b) at a prescribed position close to rotor shaft (2a) is disposed within armature (1) provided with armature winding (1b), a brushless DC motor characterized by permanent magnet (2d) being disposed near the surface of rotor (2) corresponding to the end of each permanent magnet (2b) in the direction of rotation so that the gap magnetic flux density distribution between armature (1) and rotor (2) is concave-shaped.

Detailed Description of the Invention

Field of Industrial Application

The present invention relates to brushless DC motors and in particular to a brushless DC motor wherein a rotor provided with a permanent magnet at a prescribed location close to a rotor shaft is disposed within an armature provided with an armature winding.

Prior Art

Brushless DC motors which can be operated at higher efficiencies than AC motors have been proposed for some time, and their use in home appliances such as air-conditioners has been studied. Since cost cannot be ignored when considering use in home appliances, a construction that has been employed is to obtain the rotor position signal – theoretically indispensable in brushless DC motors – from the motor terminal voltages. This construction can be broadly classified into (1) those that obtain the rotor position signal from the fundamental wave of the motor speed electromotive force (see Fig. 3) and (2) those that obtain the rotor position signal from the third-order harmonic component of the motor speed electromotive force waveform (see Fig. 4). Note that inverter circuits are not shown in Fig. 3(A) and Fig. 4(A).

With the circuit shown in Fig. 3(A), the period during which continuity is present in the inverter is set to an electrical angle of 120° to provide a motor terminal open mode period as shown in Figs. 3(B) and (C). An RC circuit is used to detect the fundamental wave Su (see Fig. 3(D)) from the motor speed electromotive force Vu (see Fig. 3(E)) that is generated during the said period. The rotor position signal is then obtained from the said fundamental wave Su. Fig. 3(F) shows motor current Iu. The suffix "u" denotes the U phase.

Even though the circuit configuration is simple with this approach, since the inverter output waveform is controlled only using an electrical angle of 120° , it is not possible to fully utilize the efficiency and the performance of a brushless DC motor. With the circuit shown in Fig. 4(A), the period during which continuity is present in the inverter is set to an electrical angle of 180° as shown in Figs. 4(B) and (C). The neutral point voltage Vm of a resistance that is Y-connected to the output terminals of the inverter circuit and the neutral point voltage Vn of a motor winding that is Y-connected are supplied to an operational amplifier to detect the differential voltage Vn – Vm (third-order harmonic components of the motor speed electromotive force waveform) (see Fig. 4(D)). The rotor position signal is obtained from the differential voltage Vn – Vm. Fig. 4(F) shows motor current Iu. The suffix "u" denotes the U phase.

With this approach, even though it is necessary to provide a neutral point motor terminal, since the inverter output waveform can be controlled using an electrical angle of 180°, it is possible to fully utilize the efficiency, performance and the like of a brushless DC motor. Fig. 5(A) shows the efficiency of brushless DC motors that are driven with the circuits shown in Fig. 3(A) and Fig. 4(A). Fig. 5(B) shows the operating ranges. Here, the brushless DC motor that is used (hereinafter "embedded DC motor") has a rotor provided with a permanent magnet at a prescribed position close to the rotor shaft. In both figures, "a" identifies a continuity period of 180° , "b" 120° and "c" 150° . The circuit shown in Fig. 4(A) was used for "a" and "c" while the circuit shown in Fig. 3(A) was used for "b."

As Figs. 5(A) and (B) show, the circuit shown in Fig. 4(A) is superior to that shown in Fig. 3(A) in terms of both efficiency and operating range. The use of the circuit configuration shown in Fig. 4(A) is therefore preferable for driving an embedded DC motor. The reason is that providing a d-axis current (with non-salient poles, a current that is 90° advanced with respect to the motor speed electromotive force) generates a reluctance torque that is added to the magnet torque (improving efficiency) and generates an armature magnetic field that weakens the magnetic flux created by the permanent magnet (see Fig. 6). This suppresses the speed electromotive force at high speeds and allows operating beyond the inverter voltage saturation point (expanding the operating range). Fig. 6(A) is a schematic view showing the relationship between the magnet's magnetic flux and the armature's magnetic flux. Fig. 6(B) shows the 3-phase (u-phase, V-phase and W-phase) armature currents. Fig. 6(C) shows the change in magnetic flux density of the permanent magnet (dotted line)

and the magnetic flux density created by the armature current (solid line) as a function of the rotation angle (electrical angle) of the rotor while running a d-axis current (for example, by running an armature current for each phase at time t = t0 in Fig. 6(B) for the rotor position shown in Fig. 6(A)). Fig. 6(D) shows the change in magnetic flux density of the permanent magnet (dotted line) and the magnetic flux density created by the armature current (solid line) as a function of the rotation angle (electrical angle) of the rotor while running a q-axis current (for example, by running an armature current for each phase at time t = t1 in Fig. 6(B) for the rotor position shown in Fig. 6(A)). As this figure shows, only the d-axis current contributes to the magnetic flux that is linked to the armature (stated otherwise, the value that is obtained by integrating the magnetic flux density "be" over ¸ = 0 through π in Fig. 6(C) or Fig. 6(D)), and the magnetic flux that is linked to the armature has the effect of weakening the magnetic flux created by the permanent magnets (hereinafter this effect is referred to as the "flux weakening effect").

Problem to be Solved by the Invention

In consideration of the above, what is required for operating embedded DC motors at the maximum efficiency and controlling and expanding their operating range is to increase the d-axis current. However, if the d-axis current is increased, the effect of the armature magnetic field that is created by the d-axis current would reduce not only the fundamental wave but also the third-order harmonic components of the motor speed electromotive force waveform. This reduces the noise margin of the rotor position detection signal and raises the possibility of a malfunction causing a loss of speed of the embedded DC motor. Stated otherwise, the reliability of the embedded DC motor decreases.

This means that ensuring the reliability requires controlling the inverter so that the d-axis current is kept below the optimum value, but this also means an inability to operate at the maximum efficiency or fully expand the operating range. Also if the specifications of the motor are such that the salient pole coefficient (Lq/Ld) is large and the motor speed electromotive force constant with respect to the fundamental component becomes roughly equal to the product of Ld and Id when operating at the maximum efficiency, the magnetic flux produced by the permanent magnets is roughly 0. Theoretically speaking, this means that controlling the motor is difficult with the method wherein the position detection signal is obtained from the speed electromotive force. Lq represents the q-axis inductance; Ld, the d-axis inductance; and Id, the d-axis current.

Object of the Invention

The present invention has been made in light of the afore-described problems. It is the object of the present invention to provide an embedded DC motor wherein the level of third-order harmonic components of the motor speed electromotive force waveform is raised so that the rotor position detection signal can be reliably obtained while keeping the d-axis current at the optimum value and keeping the motor within its operating range.

Means for Solving the Problem

In a brushless DC motor wherein a rotor containing a permanent magnet at a prescribed position close to a rotor shaft is disposed within an armature provided with an armature winding, the brushless DC motor of claim 1 has a permanent magnet disposed near the surface of the rotor corresponding to the end of each permanent magnet in the direction of rotation so that the gap magnetic flux density distribution between the armature and the rotor is concave-shaped.

Operation

In a brushless DC motor wherein a rotor containing a permanent magnet at a prescribed position close to a rotor shaft is disposed within an armature provided with an armature winding, the brushless DC motor of claim 1 has a permanent magnet disposed near the surface of the rotor corresponding to the end of each permanent magnet in the direction of rotation so that the gap magnetic flux density distribution between the armature and the rotor is concave-shaped. This allows the gap magnetic flux density distribution between the armature and the rotor to be concave-shaped. At the same time, the level of the third-order harmonic components of the motor speed electromotive force waveform can be raised when within the motor's operating range while increasing the reliability of the rotor position detection signal when the said signal is obtained from the third-order harmonic components of the motor speed electromotive force waveform. The efficiency of the

motor can also be increased, and the different controls in expanding the operating range can be optimized. Furthermore, since the shape of the gap magnetic flux density becomes concave, control can be exercised even with motor specifications wherein the salient pole coefficient is large and Ke = Ld ·Id for the fundamental wave components during maximum efficiency operation.

Embodiments

An embodiment of the present invention is described next in detail with reference to the attached figures showing the embodiment. Fig. 1 shows a partial schematic view of an embodiment of a brushless DC motor according to the present invention. The said brushless DC motor is equipped with armature 1 and rotor 2. Armature 1 is provided with a plurality of slots 1a on its inner surface, and a three-phase armature winding 1b is contained within slot 1a. U, V and W identify the phases, and + and – indicate the direction of the armature winding 1b. Rotor 2 is equipped with main permanent magnet 2b which is contained within the permanent magnet containment space that is formed at a prescribed location close to rotor shaft 2a. [Rotor 2] is also equipped with magnetic flux short-circuit prevention spaces 2c which extend outwardly towards the outer perimeter of rotor 2 from the ends of the permanent magnet containment space extending in the direction of rotation of the rotor. Furthermore, in a region that is partitioned by a pair of magnetic flux short-circuit prevention spaces 2c, [rotor 2] is also provided with auxiliary permanent magnets 2d that extend in the direction of rotation of the rotor over a prescribed length at prescribed locations near the outer periphery. The locations of the magnetic poles of the said auxiliary permanent magnets 2d are set to have the effect of increasing the gap magnetic flux with respect to the magnetic flux created by the main permanent magnet 2a.

In Fig. 2 which also shows armature 1 hypothetically opened and spread out, as the waveform of the solid lines in Fig. 2 show, the gap magnetic flux density "be" (,) corresponding to the rotation angle (electrical angle) of rotor 2 increases where auxiliary permanent magnets 2d exist, thereby resulting in a shape that is generally concave. What happens in fact is that since the apparent gap length becomes longer in slot 1a, reluctance increases, resulting in the gap magnetic flux density to become that shown by the dotted lines in Fig. 2. Taking the average of these results in the waveform shown by the solid lines.

Letting "L" represent the length (stacked thickness of the motor) of rotor 2, "n" the number of turns, "Ψe" the magnetic flux, "be" the magnetic flux density, "k" the order of the harmonic component, "Bek" the amplitude of a harmonic component, "Bem" the maximum amplitude of magnetic flux density "be," "β" the angle representing the concave period, "a" the percentage reduction in the iteration of the concave portion and "τ" the period during which the magnetic flux density is 0, the number of magnetic fluxes that are linked with the U-phase winding is represented by equation 1.

Equation 1: [See original, page 4, top 5 lines. The Japanese word in line 5 is "where."]

Equation 2 shows the motor speed electromotive force that is induced in the U-phase winding.

Equation 2: [See original, page 4, lines 11 and 12.]

Equation 3 shows the amplitude of the respective harmonic components.

Equation 3: [See original, page 4, lines 13 and 16. The Japanese word in line 16 is "where."]

The number of magnetic fluxes and the motor speed electromotive force linked with windings of other phases can also be obtained in the same manner. More specifically, whereas for a brushless DC motor without auxiliary permanent magnets 2d, Bem was 1.08[T], $\tau = 15°$, Be1 = 1.33[T] and Be3 = 0.32[T], the corresponding values were Bem = 1.27[T], $\tau = 15°$, $\beta = 30°$, a = 0.646, Be1 = 1.41[T] and Be3 = 0.52[T]. As this specific example shows, by providing auxiliary permanent magnets 2d to rotor 2, the third-order harmonic components increased by approximately 60% but there was no change in the fundamental wave component and the third-order harmonic component that are included in the magnetic flux density distribution created by armature current id.

Therefore, the approximately 60% increase in the third-order harmonic component that serves as the

source of the rotor position detection signal means a greater noise margin and a greater reliability of the rotor position detection signal. A consequence of this is an improvement in the motor's efficiency and an optimization of control over the expansion of the operating range. Also since the shape of the gap magnetic flux density is made concave by the provision of auxiliary permanent magnets 2d, control is possible even with motor specifications wherein the salient pole coefficient is large and $Ke = Ld \cdot Id$ for the fundamental wave component during maximum efficiency operation.

The foregoing explanation applies to the case wherein auxiliary permanent magnets 2d were provided to rotor 2 to make the gap magnetic flux density concave-shaped. However, by changing the shape of the armature core, the manner in which the armature windings are wound and the like, it is possible to change the shape of the magnetic flux density created by the armature to be convex. The same effects as those achieved with the above embodiment can be achieved.

Effects of the Invention

The invention of claim 1 provides unique effects as described below. The level of the third-order harmonic components of the motor speed electromotive force waveform in the motor operating range is raised. If the rotor position detection signal is obtained from the third-order harmonic components of the motor speed electromotive force waveform, this improves the reliability of the rotor position detection signal which, in turn, improves the motor's efficiency and allows the controls for expanding the operating range to be optimized. Furthermore, since the magnetic flux density is made concave, control is possible even with motor specifications wherein the salient pole coefficient is large and $Ke = Ld \cdot Id$ for the fundamental wave component during maximum efficiency operation.

Brief Explanation of the Figures

Fig. 1 is a partial schematic view of one embodiment of a brushless DC motor according to the present invention.

Fig. 2 shows the change in gap magnetic flux density.

Figs. 3 show the construction of an apparatus wherein the fundamental component of the motor speed electromotive force is used to obtain the rotor position signal and also the shapes of the signals at different points.

Figs. 4 show the construction of an apparatus wherein the third-order harmonic component of the motor speed electromotive force is used to obtain the rotor position signal and also the shapes of the signals at different points.

Figs. 5 show the efficiency characteristic and the operating range.

Figs. 6 show the relationship between the magnet's magnetic flux and the armature's magnetic flux and also the effects of the armature current on the motor speed electromotive force.

Explanation of the reference numbers
1. Armature
1b. Armature winding
2. Rotor
2a. Rotor shaft
2b. Main permanent magnet
2d. Auxiliary permanent magnet

Fig. 1
1. Armature
1b. Armature winding
2. Rotor
2a. Rotor shaft
2b. Main permanent magnet
2d. Auxiliary permanent magnet

Fig. 2

Fig. 3
Fig. 4

Fig. 5
[Plots efficiency (%) along the y-axis and rotation speed (rps) along the x-axis. Plots load torque (kg-cm) along the y-axis and rotation speed (rps) along the x-axis.]

Fig. 6
[q-axis, d-axis, armature magnetic flux, magnet magnetic flux, linked magnetic flux]